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Experimental study and energy saving analysis of a novel radiant ceiling heating system

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Abstract: In order to have an in-depth understanding of the metal ceiling radiant panel with capillary tubes, a radiant ceiling heating system is constructed to study the actual heating performance and thermal comfort by experiments. In addition, the energy saving potential of the novel heating system is discussed in terms of the COP (coefficient of performance) of the ground source heat pump and the exergy efficiency of the radiant terminal. The results indicate that the heating system shows high thermal stability and thermal comfort. When the system reaches a stable condition, the radiant heat transfer accounts for 62.7% of the total heat transfer, and the total heat transfer can meet the heating demands of most buildings. Compared to a radiant floor heating system, it offers advantages in a shorter preheating time, a lower supply water temperature and a stronger heating capability. The COP of the ground source heat pump is increased greatly when the supply water temperature is 28 to 33 ℃, and the exergy efficiency of the metal ceiling with capillary tubes is 1.6 times that of the radiant floor when the reference temperature is 5 ℃. The novel radiant ceiling heating system shows a tremendous energy saving potential.

Key words: radiant heating system; capillary tube; heating performance; energy saving; exergy efficiency

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The radiant air conditioning system, in accordance with sustainable development, is a new green system with low energy consumption, high thermal comfort and health promoting. Unlike the heat transfer method of the conventional air conditioning system, it provides a healthy and comfortable environment for people by the radiant heat transfer of a radiant ceiling system.

There have been many studies on the radiant ceiling system used for cooling in summer. Catalina et al. [1] evaluated the thermal comfort in a test room equipped with a cooling ceiling by combining CFD and an experimental study. Causone et al. [2] calculated the heat transfer coefficients between the radiant ceiling and room in the typical occupancy conditions of an office or residential building. Tian et al. [3] explored the actual cooling performance of radiant ceiling panels without mechanical ventilation. Fonseca et al. [4] developed a model of hydronic radiant ceiling panels using transient-state analysis, and the behavior of the hydronic ceiling system and the interactions with its environment have been experimentally and numerically evaluated. For the radiant ceiling cooling system, the biggest problem that may occur in the process of the actual operation is condensation on the ceiling. There have been some available strategies to solve this problem, such as low-temperature dehumidification[5], solid and liquid desiccant systems[6−7]. Now, the radiant ceiling cooling system is widely used in Europe[8] and China[9].

However, radiant ceiling panels can also be used for heating in winter. There have been a few studies on radiant ceiling heating systems. Miriel et al. [10] developed simulation models for the performance of radiant ceiling heating systems with the simulation program TRNSYS. Rahimi et al. [11] constructed a model enclosure representing a room equipped with a radiant ceiling heating system and investigated the participation of the radiation and free convection in the heat transfer from the ceiling surface of a room to other internal surfaces. Tye-Gingras et al. [12] reported the comfort and energy consumption of hydronic heating radiant ceilings and walls based on the CFD analysis. In this paper, the metal panel with capillary tubes, a novel modularized radiant terminal, is introduced. The experimental system has been constructed to study the actual heating performance and thermal comfort, and the energy saving potential of the metal ceiling radiant heating system with capillary tubes is also analyzed.

1 Experimental System

1.1 Test room and heating system

Fig. 1 shows the pictures of the modularized metal panel with capillary tubes. The metal panel is made of aluminum material painted white. The capillary tube, which is made of PPR plastic, is placed in the metal panel and fixed by a copper plate. There are four screw thread interfaces at each end of the capillary tube, which are used to achieve assembly of the modularized metal panel with capillary tubes. The size of the metal panel is

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0.6 m × 0.6 m. The outside diameter of the capillary tube is 4 mm and the wall thickness is 0.8 mm. The distance between the adjacent supply water tubes (or back water tubes) is 4 cm, and the distance between a supply water tube and the adjacent back water tube is 1.5 cm. In order to study the actual heating performance, the experiment was conducted in an office room (6.0 m × 3.0 m × 2.8 m). The north wall of the test room is an exterior wall with a 1.8 m × 1.5 m glass window and the south wall is near the corridor. No air conditioning is provided to any adjacent rooms. The radiant ceiling in the test room is made of several block metal panels and the total area is 15.12 m^2. Meanwhile, a radiant floor heating system was constructed in the office room to be compared to the metal ceiling radiant heating system.

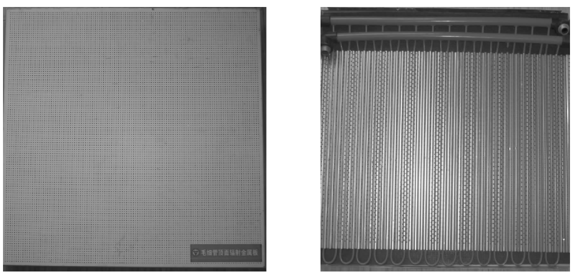

Fig. 1 Pictures of the metal panel with capillary tubes. (a) Obverse side; (b) Reverse side

Fig. 2 shows the heating system. The production of the hot water is made by a ground source heat pump unit. The radiant ceiling is divided into three loops. The three capillary tube loops are connected in parallel and fed by a flat-plate exchanger. The supply water temperature is controlled by 3-way valves on each side of the heat exchanger.

1.2 Measuring instruments and testing scheme

Tab. 1 shows the measurement parameters and instrument performance. Measurement parameters include the water flow, supply and return water temperatures, outdoor temperature and humidity, wall surface temperatures and distribution of indoor air temperatures. The distribution of the temperature measuring points is shown in Fig. 3. Due to the thermal inertia of the radiant heating system, the change in the indoor temperature field is not noticeable in a short time. So the measurement parameters were measured every 10 min.

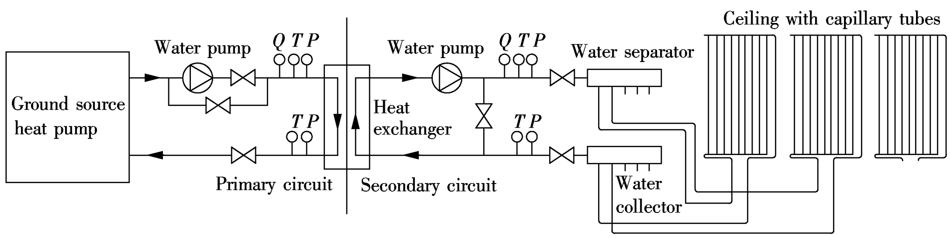

Fig. 2 Heating system

Tab. 1 Measurement parameters and instrument performance

Measurement parameter	Wall surface and indoor air temperatures	Outdoor temperature and humidity	Water flow	Supply and return water temperatures
Instrument	K-type thermocouple	Temperature and humidity sensor	Electromagnetic flow meter	Platinum thermal resistor
Range	−200 to 350 ℃	−40 to 120 ℃, 0 to 100% RH	0.3 to 10 m^3/h	−50 to 500 ℃
Accuracy	±0.1 ℃	±0.2 ℃, ±1% RH	±0.2%	±0.1 ℃

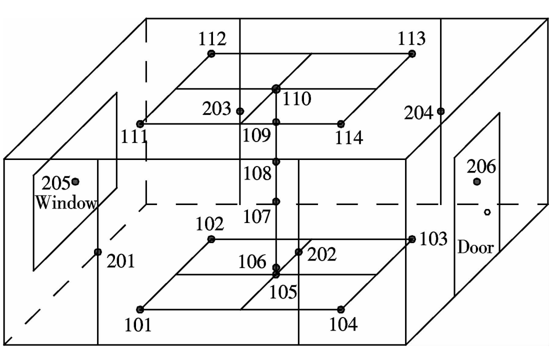

Fig. 3 The distribution of temperature measuring points

2 Results and Discussion

2.1 Heating performance and thermal comfort in a heating test

Ceiling, floor and indoor air temperatures were measured from 8:00 to 22:00 (8:00 on, 18:00 off), as shown in Fig. 4. The supply water temperature is 32.4 ℃ and the water flow is 1.2 m^3/h. The atmosphere temperature changes from 0.8 to 3.7 ℃, and the average temperature is 2.4 ℃. When the system starts, the ceiling temperature increases rapidly from 5.9 to 25.2 ℃ in 1 h and then remains at about 26 ℃. There is a temperature difference of 6.4 ℃ between the ceiling and supply water temperatures. The indoor air temperature reaches 17.3 ℃ after the system runs for 2 h, which is able to meet the thermal comfort requirements (ASHRAE 55—2004 standard[13]). Compared to the radiant floor and other types of radiant ceiling heating systems, it has a shorter preheating time. So this system is more suitable for places requiring intermittent heating. When the system reaches a stable condition, it shows fine thermal stability. The average indoor temperature is 18.2 ℃ and the average floor temperature is 19.5 ℃. There is a temperature difference of 1.3 ℃ between the indoor air and floor temperatures. The small temperature difference creates high thermal comfort. When the system is off, the ceiling temperature decreases quickly, while the indoor temperature decreases slowly to 12 ℃ after the system is off for 4 h.

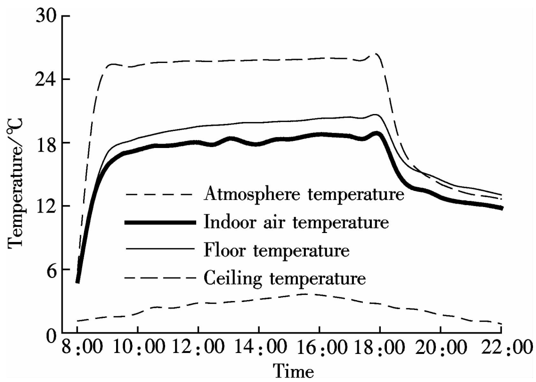

Fig. 4 Ceiling, floor and indoor air temperatures in a heating test

The heat transfer of the ceiling consists of two parts: the radiant heat transfer between the ceiling and walls, and the convective heat transfer between the ceiling and indoor air. The radiant heat flow is calculated according to the Gebhart Law[14]. In a closed room which is composed of n surfaces, the net radiant heat flow of surface j is obtained by

$$Q_{R,j} = \sigma\varepsilon_j T_j^4 F_j - \sum_{i=1}^{n} B_{i,j}\sigma\varepsilon_i T_i^4 F_i \tag{1}$$

$$\begin{bmatrix} \phi_{1,1}\rho_1 - 1 & \phi_{1,2}\rho_2 & \cdots & \phi_{1,n}\rho_n \\ \phi_{2,1}\rho_1 & \phi_{2,2}\rho_2 - 1 & \cdots & \phi_{2,n}\rho_n \\ \vdots & \vdots & & \vdots \\ \phi_{n,1}\rho_1 & \phi_{n,2}\rho_2 & \cdots & \phi_{n,n}\rho_n - 1 \end{bmatrix} \begin{bmatrix} B_{1,j} \\ B_{2,j} \\ \vdots \\ B_{n,j} \end{bmatrix} = \begin{bmatrix} -\varepsilon_j\phi_{1,j} \\ -\varepsilon_j\phi_{2,j} \\ \vdots \\ -\varepsilon_j\phi_{n,j} \end{bmatrix} \tag{2}$$

where σ is the Boltzmann constant; F_i is the area of surface i; $B_{i,j}$ is the absorption factor of surface i to surface j; $\phi_{i,j}$ is the angle factor of surface i to surface j; ρ_i is the reflectance of surface i; ε_i is the emissivity of surface i.

The convective heat flow is calculated by[15]

$$Q_c = \alpha F_c (t_c - t_{in}) \tag{3}$$

where α is the convective heat transfer coefficient between the ceiling and indoor air; F_c is the area of the ceiling; t_c is the temperature of ceiling; t_{in} is the indoor air temperature.

The convective heat transfer coefficient α is calculated by the following equations:

$$Gr = \frac{g\alpha\Delta t l^3}{\nu^2} \tag{4}$$

$$Nu = 0.15(GrPr)^{1/3} \tag{5}$$

$$\alpha = \frac{Nu\lambda}{l} \tag{6}$$

When the system reaches stable conditions, the radiant heat flow is about 57.2 W/m^2. The convective heat flow is about 33.6 W/m^2 and the total heat transfer of the ceiling is about 90.8 W/m^2. The radiant heat flow accounts for 63% of the total, which is much greater than the convective heat flow. The total heat transfer of the ceiling can meet the heating demands of most buildings.

Fig. 5 shows the distribution of the indoor vertical temperature at one time after the system reaches stable conditions. The temperature gradient near the ceiling is large, which indicates that the ceiling surface has a strong convective heat transfer. The temperature is almost a linear distribution from 0.1 to 2.2 m and the temperature gradient is small. There is a certain temperature rise from 0.1 m to the ground. ASHRAE 55—2004 standard considers that a comfortable temperature difference in the area of human activities (0.1 to 1.8 m) should be less than 3 ℃. In the test, there is a temperature difference of 2.2 ℃ in the area of human activities, which meets the ASHRAE 55—2004 standard on human comfort requirements.

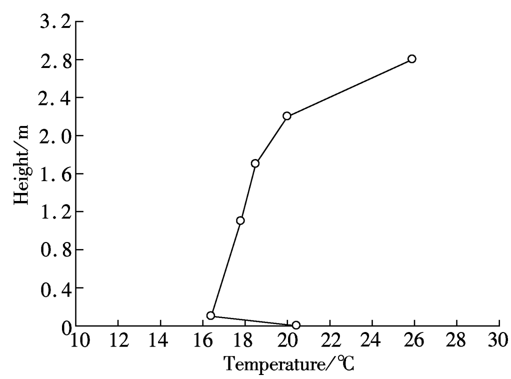

Fig. 5 Indoor vertical temperature distribution

PMV (predicted mean vote) and PPD (predicted percent dissatisfied) are used to describe and evaluate thermal comfort in the international standard ISO 7730[16]. The recommended value of PMV given by ISO 7730 is $-0.5 \leqslant \text{PMV} \leqslant +0.5$. Correspondingly, PPD $\leqslant$ 10%, which means that the environment is allowed to be judged unsatisfactory by no more than 10% people.

In a radiant heating system, the radiant heat transfer between the inner surface of the building envelope and bodies has a significant influence on thermal comfort. In order to consider the effect of radiation comprehensively, the mean radiant temperature (MRT) and operative temperature (OT) have been put forward to evaluate human thermal comfort[17]. MRT and OT are calculated by

$$t_m = \frac{\sum F_i t_i}{\sum F_i} \tag{7}$$

$$t_o = \frac{1}{2}(t_{in} + t_m) \qquad (8)$$

where t_m is the mean radiant temperature; F_i is the area of surface i; t_i is the temperature of surface i; t_o is the operative temperature.

MRT, OT, PMV and PPD are shown in Tab. 2. All the indices are average in the stable condition of the system. The difference between the indoor temperature and MRT is 2.4 ℃, and the difference between the indoor temperature and OT is 1.2 ℃. This verifies that the radiant ceiling heating system can create the same thermal comfort with a lower indoor design temperature. PMV and PPD are in the recommended value range given by ISO 7730 and meet the requirements for thermal comfort.

Tab. 2 Thermal comfort indices

Parameter	Indoor temperature/℃	Mean radiant temperature/℃	Operative temperature/℃	PMV	PPD/%
Value	18.2	20.6	19.4	0.38	8.07

2.2 Variable supply water parameters

In order to further study the heating performance of the system, variable supply water conditions are studied. Tested supply water temperatures are 25, 30, 35 and 40 ℃. Water flow is 1.2 m^3/h. Indoor, ceiling and operative temperatures under different supply water temperatures are shown in Fig. 6. The ceiling temperature increases almost linearly with the rise of supply water temperature, and these two temperatures maintain a difference of 5 to 7 ℃. When the supply water temperature is in the range of 30 to 35 ℃, the indoor temperature shows a clear upward trend. However, the upward trend is not obvious outside this temperature range. So adjusting the supply water temperature outside this range is not meaningful. The change trend of the operative temperature is consistent with but higher than the indoor temperature. It is noted that the difference between the operative temperature and indoor temperature increases gradually with the increase in the water temperature. This is because the walls and floor temperatures increase with the increase in water temperature and then increase the share of the radiation heat quantity. In addition, considering the thermal comfort and energy saving, the optimal supply water temperature is in the range of 28 to 33 ℃. While the floor radiant heating system is used to meet the same thermal comfort, the supply water temperature is required to be 40 to 50 ℃. Compared to the floor radiant heating system, the novel heating system requires a lower supply water temperature.

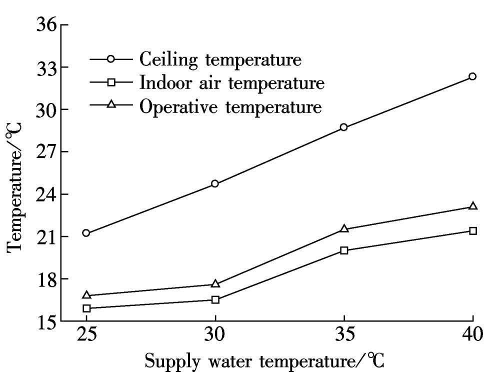

Fig. 6 Ceiling, indoor air and operative temperatures under different supply water temperatures

When the water temperature is 30 ℃, tested water flows are 0.8, 1.0, 1.2 and 1.4 m^3/h. Indoor, ceiling and operative temperatures are shown in Fig. 7. The changing trends of three temperatures are not obvious with the change in the water flow. Therefore, water temperature has a greater impact on the heating performance of the metal ceiling radiant heating system with capillary tubes than water flow.

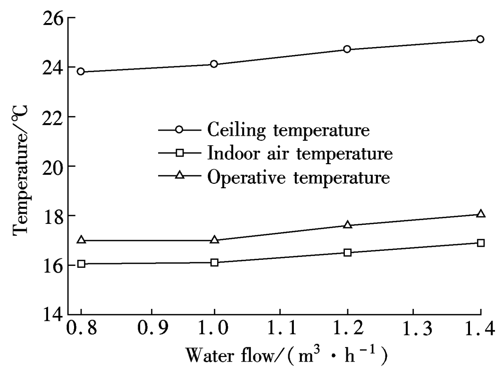

Fig. 7 Ceiling, indoor air and operative temperatures under different water flows

3 Analysis of Energy-Saving Potential

According to the discussion above, it is clear that the metal ceiling heating system with capillary tubes calls for a lower supply water temperature compared to the floor radiant heating system. Thus, this system has an obvious energy-saving effect. Now, the energy-saving potential of this system is analyzed from two aspects in comparison with the floor radiant heating system: the COP of the ground source heat pump unit and the exergy efficiency of the radiant terminal.

3.1 COP of the ground source heat pump

The supply water temperature of the metal ceiling radiant heating system with capillary tubes is 28 to 33 ℃, while the floor radiant heating system is 40 to 50 ℃. When the water flow of load side is 2.4 m^3/h and the water flow of water source is 3.4 m^3/h, the COP of the ground source heat pump changing with different water supply temperatures is shown in Fig. 8.

The COP of the ground source heat pump declines gradually with the rise of the supply water temperature. When the supply water temperature is 32 ℃, the COP is 5.6. However, when the supply water temperature is 44

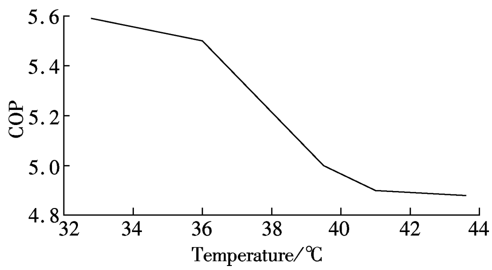

Fig. 8 COP of ground source heat pump changing with the supply water temperature

℃, the COP is 4.9. The COP increases by 14.3% when there is a temperature difference of 12 ℃ between the different supply water temperatures. Thus, with the ground source heat pump as the heat source, the metal ceiling radiant heating system with capillary tubes has a remarkable energy saving potential.

3.2 Exergy analysis of the radiant terminal

According to the definition of exergy, exergy is expressed as[18]

$$e_x = w_{max} = h - h_0 - T_0(s - s_0) = C_p(T - T_0) - C_p \ln \frac{T}{T_0} \tag{9}$$

where e_x is the specific exergy of the working medium; w_{max} is the maximum specific work; T_0 is the environment temperature or reference temperature; T is the inlet temperature; C_p is the specific heat at constant pressure.

The supply and return water temperatures of the floor radiant heating system are 45 and 42 ℃, respectively. The supply and return water temperatures of the metal ceiling radiant heating system are 32 and 30 ℃, respectively.

For the metal ceiling radiant heating system, the consumed exergy is

$$\Delta E_c = m_c(e_{x,32\,℃} - e_{x,30\,℃}) \tag{10}$$

For the floor radiant heating system, the consumed exergy is

$$\Delta E_f = m_f(e_{x,45\,℃} - e_{x,42\,℃}) \tag{11}$$

When the heating load of the metal ceiling radiant heating system is equal to that of the floor radiant heating system, the medium flow is obtained by

$$Q = C_p m \Delta t \tag{12}$$

$$\frac{m_f}{m_c} = \frac{2}{3} \tag{13}$$

Under the premise of the same heating effect, the earning exergy of the two heating systems has the following relationship:

$$\Delta E_{f,gain} = \Delta E_{c,gain} \tag{14}$$

In order to compare the exergy efficiency of the radiant ceiling and radiant floor units, η is defined as the relative exergy efficiency.

$$\eta = \frac{E_{c,gain}/\Delta E_c}{E_{f,gain}/\Delta E_f} = \frac{\Delta E_f}{\Delta E_c} \tag{15}$$

The reference temperature is an important parameter to calculate the exergy efficiency. Different reference temperature influences the calculation result of the relative exergy efficiency. Fig. 9 shows the relative exergy efficiency changing with the reference temperature. The relative exergy efficiency rises gradually with the rise of the reference temperature. The exergy efficiency of the metal ceiling with capillary tubes is 1.6 times that of the radiant floor when the reference temperature is 5 ℃.

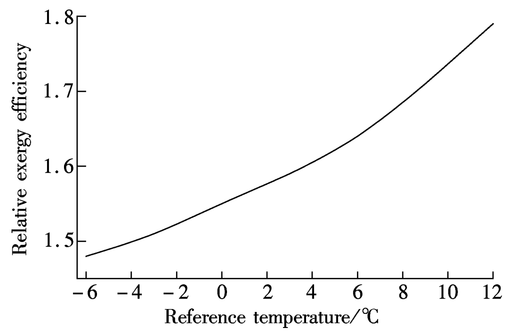

Fig. 9 Relative exergy efficiency changing with the reference temperature

4 Conclusion

The metal ceiling radiant heating system with capillary tubes was constructed to study the actual heating performance, thermal comfort and energy saving potential. The system shows fine thermal stability and thermal comfort with a uniform indoor air temperature distribution in vertical directions in a heating test. When the system reaches a stable condition, the radiant heat transfer accounts for 62.7% of the total heat transfer and the total heat transfer can meet the heating demands of most buildings. Compared to the floor radiant heating system and other types of radiant ceiling systems, it has a shorter preheating time, a lower temperature requirement of supply water (28 to 33 ℃) and a stronger heating capability. The COP of the ground source heat pump is increased greatly when the supply water temperature is 28 to 33 ℃ compared to 40 to 50 ℃. The exergy efficiency of the metal ceiling with capillary tubes is 1.6 times that of the radiant floor when the reference temperature is 5 ℃. Therefore, the novel radiant ceiling heating system shows tremendous energy-saving potential.

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一种新型辐射吊顶采暖系统的实验研究与节能分析

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摘要：为研究毛细管-金属板吊顶的采暖特性和节能潜力，构建了毛细管-金属板辐射吊顶采暖系统，实验分析了系统的实际采暖性能和热舒适性，从地源热泵的 COP 和末端设备的火用效率探讨了系统的节能潜力. 结果表明，该采暖系统具有良好的热稳定性和热舒适性. 当系统达到稳定状态时，辐射传热占总传热量的 62.7%，并且总传热量可以满足大多数建筑的采暖需求. 与地板辐射供暖系统相比，毛细管-金属板辐射吊顶采暖系统具有预热时间短、供水温度低和采暖能力强的优势. 当供水温度为 28 ~ 33 ℃时，地源热泵的 COP 显著提高. 当基准温度为 5 ℃时，毛细管金属板辐射吊顶的火用效率是辐射地板的 1.6 倍. 该新型辐射采暖系统显示出较大的节能潜力.

关键词：辐射采暖系统；毛细管；采暖性能；节能；火用效率

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